Use of Simple X-ray Measurements in the Performance Analysis of Cryogenic RF Accelerator Cavities

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Introduction

X-ray emission by radiofrequency (RF) resonant cavities has long been known to accelerator health physicists as a potentially serious source of radiation exposure. Swanson points out the danger of klystrons and microwave cavities by stating that the radiation source term is erratic and may be unpredictable depending on microscopic surface conditions which change with time. He also states the x-ray output is a rapidly increasing function of RF input power [Swanson 1979].

At Jefferson Lab, the RF cavities used to accelerate the electron beam employ superconducting technology. X-rays are emitted at high cavity gradients, and measurements of cavity x-rays are valuable for health physics purposes and provide a useful diagnostic tool for assessing cavity performance.

The quality factor (Q) for superconducting RF resonant cavities used at Thomas Jefferson National Accelerator Facility (Jefferson Lab), is typically $5x10^9$ for the nominal design gradient of 5 MVm^{-1} [Reece 1995]. This large value for Q follows from the small resistive loss in superconducting technology. The operating frequency is 1497 MHz. In the absence of beam, the input power for a cavity is typically 750 W and the corresponding dissipated power is 2.6 W. At 5 MVm^{-1}, the input power is 3 kW fully beam loaded. At higher gradients, performance degradation tends to occur due to the onset of electron field emission from defects in the cavity.

Field Emission and Measurements of Cavity Performance

As indicated in Figure 1, there are four superconducting cavity pairs in each of Jefferson Lab's 40 cryomodules; 320 in total. Each 0.5 meter cavity provides 2.5 to 5 MV net gain to electrons in the beam and has maximum surface electric fields of 13 to 25 MV. The measurement of cavity Q versus the gradient is used to assess system performance. Superconducting cavity performance is determined by cavity wall heating as a function of accelerating voltage. Electrons liberated from field emission sites on cavity surfaces extract power from the RF field and deposit most of that power in the cavity walls, degrading Q and creating bremsstrahlung x-rays. Q measurements are performed calorimetrically and take approximately 20 minutes. Several such measurements are required on each individual cavity. There are a large number of cavities in service and, in the context of an operational accelerator, opportunities for making such measurements are rare.

The production of field emission radiation is complex. The radiation originates from the extended electron impact site, the location of which is highly dependent on both the location of the emitter on the cavity surface and the field level in the cavity. Cavity performance is frequently limited by field emission loading, and cryomodule lifetime may be limited by radiation damage to RF windows and other components. Measurement of the field emission radiation is thus a useful tool to predict the lifetime of materials used in cryomodule construction and serve as an indicator of cavity performance.

Measurement Hardware

Initially, field emission radiation measurements were made with conventional portable radiation monitoring equipment. TJNAF staff decided that a device combining radiation exposure rate measurement capability and dynamic computer interfacing was needed. Jefferson Lab staff designed, built, and installed a device christened the "Octirad". This device measures radiation at up to eight points on a cryomodule and provides both TTL logic for computer logging and switchable audio output for RF operators. Figure 2 shows the sub-circuit diagram for a channel of the Octirad. A common high voltage power supply is used to bias the GM tubes. A radiation event in the GM tube results in a negative signal on the GM tube anode. This pulse is capacitively coupled to the input of an operational amplifier, inverted, and fed to the input of a four bit binary counter. The counter feeds a 50 Ω line driver over a twisted pair to a base unit in the control room. The signals are optically isolated and shaped by a quad two input NOR gate creating a pulse with a specific weight factor in radiation dose units. The weight-factored pulse is fed to integration and isolation amplifiers which drive digital panel meters, audio amplifiers, and ADCs. Calibration for each detector is made under traceable exposure conditions (Cs-137) by adjusting the output of the driver amp. Eventually, it became more efficient to conduct cryomodule testing in-situ (in the accelerator enclosure after installation). Until the Octirad was redesigned to work with an in-situ test stand, operators were provided with six Eberline Smart Radiation Monitors, Model SRM-100, a microcomputer based portable alarming ratemeter/scaler each with an Eberline HP-270 energy compensated geiger-mueller (GM) detector. In addition, the interlock feature of the SRM-100 was used to interrupt RF at an field emission radiation exposure rate of 0.02 Gy-h-1 to limit radiation damage to components. Calibration and operations procedures used for the Octirad and SRM-100 are available on request from the authors.

Measurement Results and Discussion

Using the Octirad, post production cavity Q and field emission radiation measurements were made at six selected positions shown in Figure 1 for several cryomodules in a concrete vault. Due to the random nature of field emission radiation, it was virtually impossible to correlate any other factors but gradient and exposure rate at a given position. It was determined that field emission radiation measurements at predetermined positions were a reasonably reproducible function of cavity gradient and, as expected, highly individual to each cavity. In effect, these measurements served as signature for each cavity. It was determined that this field emission radiation signature was a convenient, time saving method of rapidly determining a diagnostic analog for field emission loading and thus, cavity Q. The computer interface to the Octirad was used to record this field emission radiation signature for each cavity at the six locations shown in Figure 1.

Figure 3 presents cavity Q and the field emission radiation dose rate at a given cavity gradient. It is evident that cavity Q degrades as field emission radiation increases and field emission radiation serves as an important performance reference point.

Recently, efforts at Jefferson Lab have improved cavity performance at higher gradients where field emission loading typically limits cavity Q. Among those efforts are helium processing. During helium processing, a cryomodule is isolated by vacuum valves and helium is introduced in the beam line inside the eight superconducting RF cavities. RF is supplied and the gradient is increased until field emission occurs. The field emitted electrons ionize the helium, forming a plasma near the emission site. It is thought that this damages the field emission site and reduces the likelihood of further field emission at that site. Such processing typically takes 1 hour per cavity. Figure 4 shows field emission radiation signature before and after helium processing as a function of cavity gradient.

Conclusions

Although field emission radiation may be erratic and unpredictable, it can serve as an important reference point if properly measured. The field emission radiation signature has provided important data at TJNAF on cavity performance during commissioning. It is also evident that the field emission radiation signatures, taken before and after helium processing, also provide a convenient way of gauging the improvement in cavity performance at higher gradients. The measurement of field emission radiation not only provides diagnostic information to operators, but also provides the Health Physicist with important data on the radiation exposure associated with powered (RF) resonant cavities. This information can be used to design shielding and, in the case of inadvertent access to areas where cryomodule testing and operation occur, it would aid in determining the extent of personnel radiation dose.

References

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Performance Experience with the CEBAF SRF Cavities. In: Proceedings of the 1995 Particle Accelerator Conference. Dallas, TX: IEEE; 95CB35843; Vol.3; 1512

Acknowledgements

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The Thomas Jefferson National Accelerator Facility was previously known as the Continuous Electron Beam Accelerator Facility (CEBAF).

Figure 1 Accelerator Components

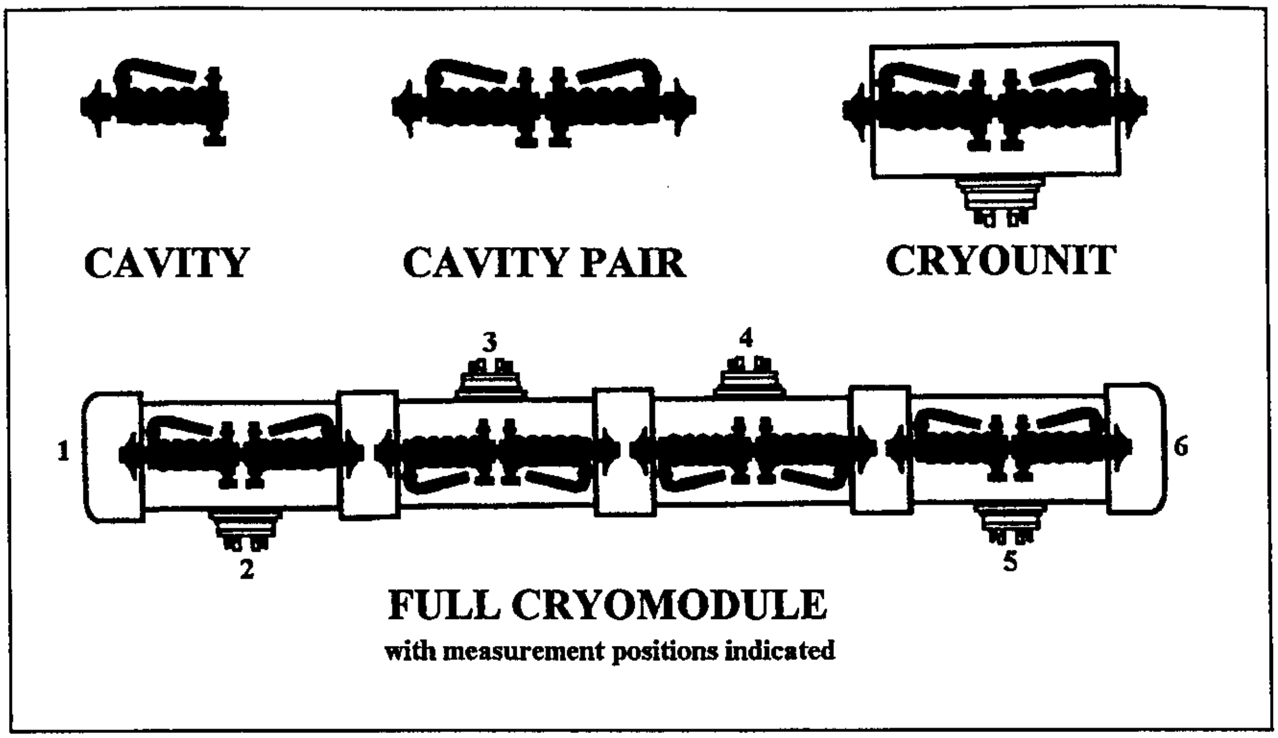


Figure 2 Octirad Subcircuit Diagram

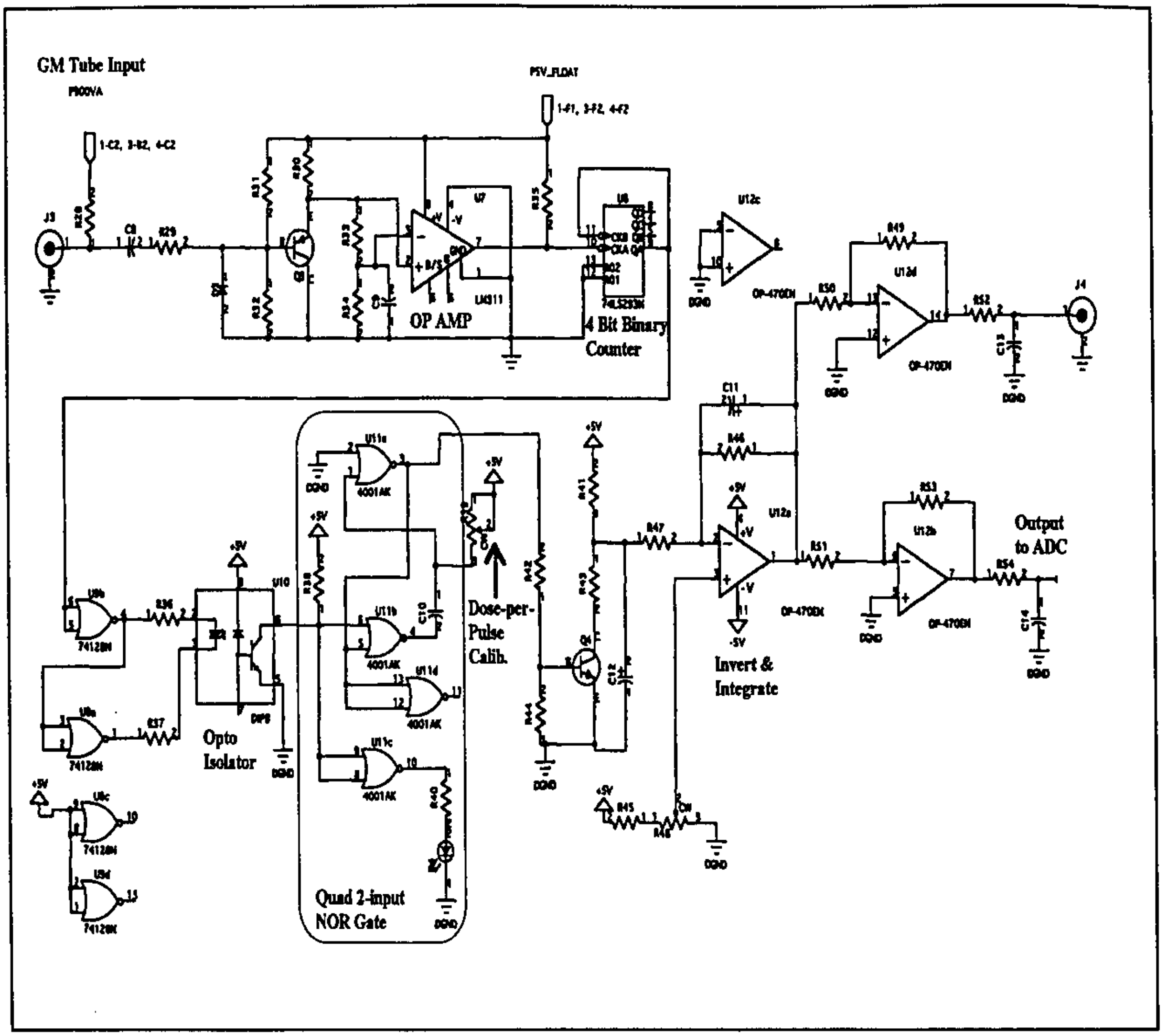
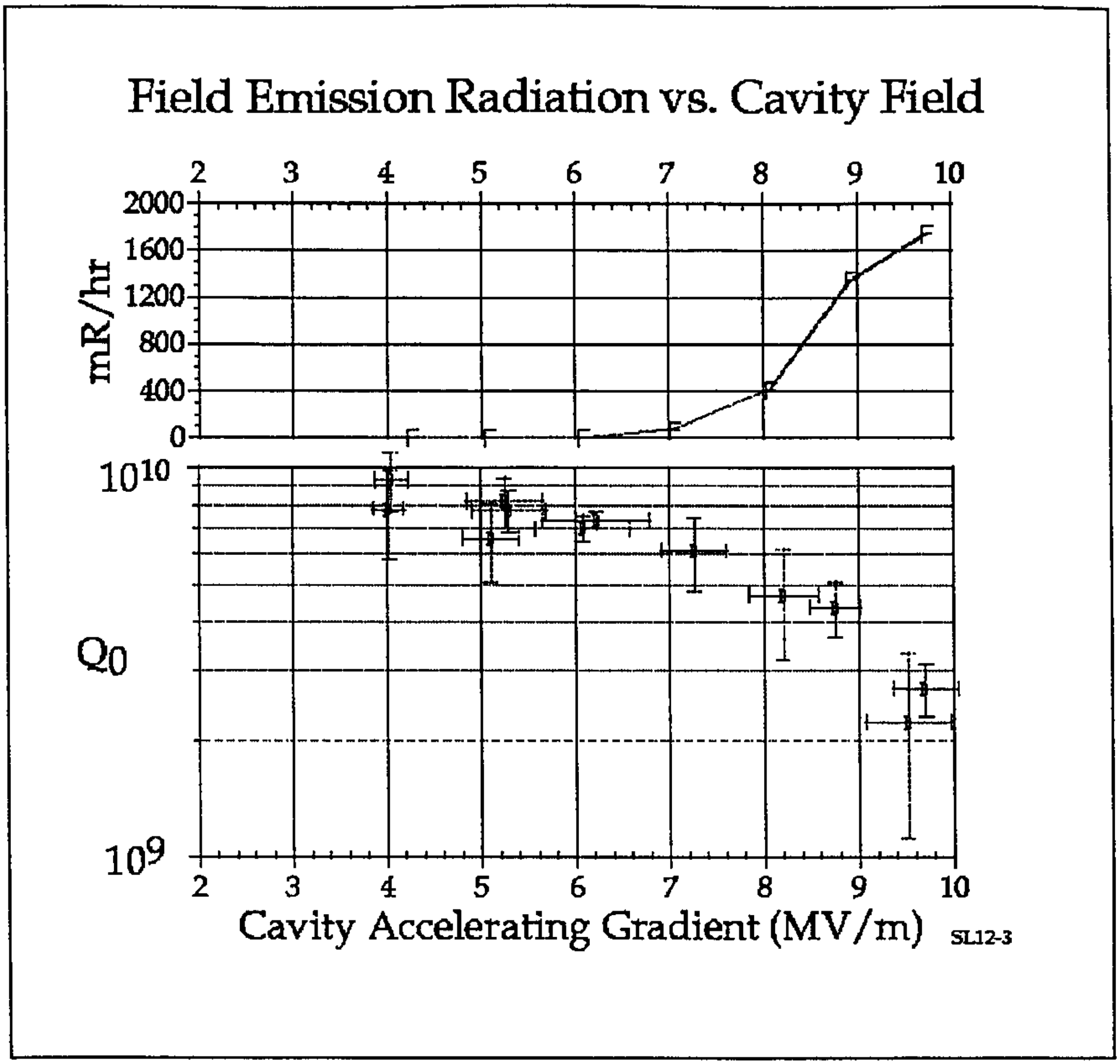
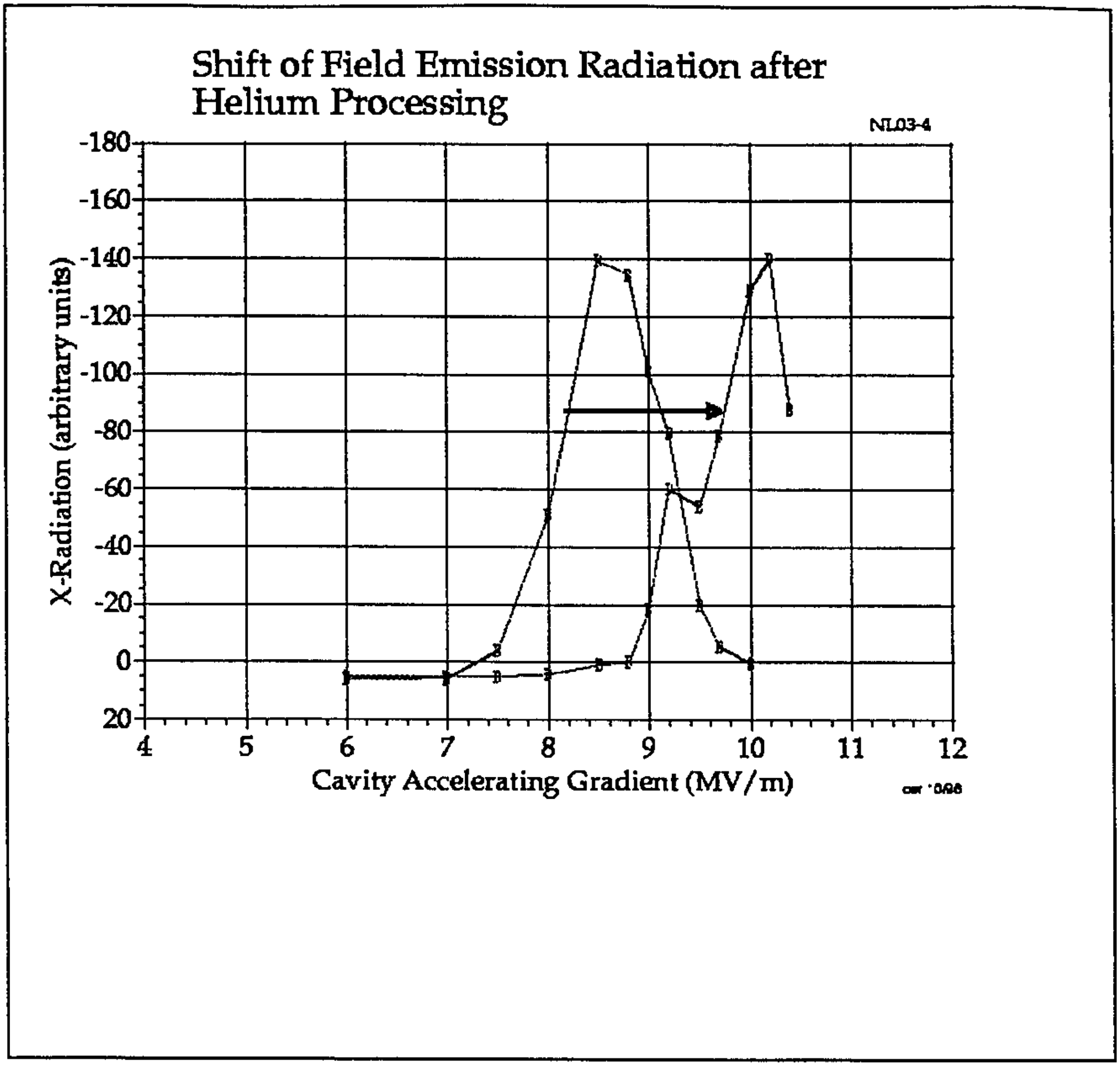


Figure 3



Field Emission Radiation vs. Cavity Field
2
3
4
5
6
7
8
9
10
2000
1600
1200
800
400
0
mR/hr
10^{10}
Q_0
10^9
Cavity Accelerating Gradient (MV/m)
SL12-3

Figure 4



Shift of Field Emission Radiation after Helium Processing
NL03-4
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
X-Radiation (arbitrary units)
4
5
6
7
8
9
10
11
12
Cavity Accelerating Gradient (MV/m)